

Aligned Molecular Clouds towards SS433 and L=348.5 degrees; Possible Evidence for Galactic "Vapor Trail" Created by Relativistic Jet

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Abstract

We have carried out a detailed analysis of the NANTEN ^{12}CO ($J=1-0$) dataset at 4-arcmin resolution in two large areas of ~ 25 square degrees towards SS433 ($l \sim 40^\circ$) and of ~ 18 square degrees towards $l \sim 348.5$, respectively. We have discovered two groups of remarkably aligned molecular clouds at high galactic latitudes of $|b| \sim 1^\circ-5^\circ$ in the two regions. In SS433, we have detected 10 clouds in total, which are well aligned nearly along the axis of the X-ray jet emanating from SS433. These clouds have similar line-of-sight velocities of $42 - 56 \text{ km s}^{-1}$ in V_{LSR} and the total projected length of the feature is ~ 300 pc, three times larger than that of the X-ray jet, at a distance of 3 kpc. Towards $l \sim 348.5$, we have detected four clouds named as MJG348.5 at line-of-sight velocities of $-80 - -95 \text{ km s}^{-1}$ in V_{LSR} , which also show alignment nearly perpendicular to the Galactic plane. The total length of the feature is ~ 400 pc at a kinematic distance of 6 kpc. In the both cases, the CO clouds are distributed at high galactic latitudes, $|b| \sim 1^\circ-5^\circ$, where such clouds are very rare. In addition, their alignments and coincidence in velocity should be even rarer, suggesting that they are physically associated. We tested a few possibilities to explain these clouds, including protostellar outflows, supershells, and interactions with energetic jets. Among them, a favorable scenario is that the interaction between relativistic jet and the interstellar medium induced the formation of molecular clouds over the last $\sim 10^{5-6}$ yrs. It is suggested that the timescale of the relativistic jet may be considerably larger, in the order of 10^{5-6} yrs, than previously thought in SS433. The driving engine of the jet is obviously SS433 itself in SS433, although the engine is not yet identified in MJG348.5 among possible several candidates detected in the X-rays and TeV gamma rays.

Key words: Radio lines: ISM — ISM: clouds — ISM: jets and outflows — starts: individual (SS433)

1. Introduction

Astrophysical jets of various scales are recognized as ubiquitous phenomena in the Universe and the physics of jets is one of the most fundamental issues in astrophysics. On stellar scales, molecular jets driven by young protostars or bipolar outflows are well known phenomena since 1980's and are believed to represent a crucial step in the proto-stellar evolution (e.g., Lada 1985; Fukui 1989; Bally et al. 2005). In addition, evolved compact stellar remnants like pulsars such as Crab pulsar, Vela pulsar, and MSH 15–52 exhibit more energetic relativistic jet with non-thermal radiation observed as pulsar-driven nebulae (e.g., Tamura et al. 1996; Weisskopf et al. 2000; Pavlov et al. 2003). Even more massive objects, black-hole candidates such as SS433 and GRS1915+105, exhibit much more energetic relativistic jet whose velocity is close to the light speed (e.g., Margon 1984; Mirabel & Rodríguez 1994). Magneto-hydrodynamical numerical simulations on these jets have been carried out by several authors mainly in order to reproduce jets themselves (e.g., Kato, Hayashi & Matsumoto 2004; Uzdensky & MacFadyen 2006). Observationally, these relativistic jets have been detected so far only through high energy phenomena including non-thermal radio emission and X-rays but their interaction with the interstellar medium were very poorly known with a possible few examples in the Galaxy (e.g., Mirabel & Rodríguez 1999); we note that interactions with the much more diffuse gas are discussed in some of the jets in external galaxies (e.g., Oosterloo & Morganti 2005; Krause et al. 2007).

Some of the relativistic jets whose origin is a neutron star or a black hole have been identified (e.g., Mirabel et al. 1992; Rodríguez, Mirabel & Martí 1992). A superluminal source, GRS1915+105, is a candidate for the relativistic jet interacting with the interstellar matter; Chaty et al. (2001) show that two IRAS point sources associated are located symmetrically at ~ 60 pc on the both sides of GRS1915+105 in a straight line. It is argued that the relativistic jet from GRS1915+105 whose velocity is estimated to be $0.92c$ may have interacted with the molecular clouds and possibly induced star formation.

SS433 is an X-ray binary system consisting of a black hole candidate or a neutron star and is accelerating relativistic jet whose speed is $0.26c$ (Margon & Anderson 1989). SS433 is also associated with a symmetric and linear jet as observed in the X-ray. The jet is extended by about 1° on each side of SS433, and the two lobes are called as East lobe and West lobe, respectively (Kotani 1997). The length of the jet is estimated to be about 40 pc on each side if we adopt a distance of ~ 3 kpc (Dubner et al. 1998). It is also known that SS 433 is located towards the center of a supernova remnant (=SNR) W50. This SNR shows a barrel-type shape in non-thermal radio continuum emission. It has features called as "ears" and "wing" along the jet axis (Elston & Baum 1987), which may be due to the interaction of the SNR with the surroundings.

The interaction of the SS433-W50 system and the surroundings has been studied by several authors. Dubner et al. (1998) studied the radio continuum emission at 1.4 GHz and the 21 cm HI emission, and noted that the HI at $V_{\text{LSR}} \sim 42 \text{ km s}^{-1}$ has a cavity-like shape surrounding the radio continuum emission, which may indicate some interaction between the HI and the SNR. On the other hand, Lockman et al. (2007) suggests that SS433-W50 interacts with the HI at $V_{\text{LSR}} \sim 75 \text{ km s}^{-1}$. Safi-Harb & Ogelman (1997) and Safi-Harb & Petre (1999) analyzed the X-ray data of ROSAT, ASCA, and RXTE, and discuss the interaction between the jet from SS 433 and the surroundings. Band (1987) and Band & Gordon (1989) studied the far infrared data taken with the IRAS and discovered some knots which may be associated with the jet, providing another piece of evidence for the interaction (Wang et al. 1990). Moldowan et al. (2005) suggest that one of the infrared objects is not correlated with the X-ray emission by the Chandra observation.

SS433 and its relationship with molecular clouds were studied by Huang et al. (1983). They claimed that the CO molecular clouds at $V_{\text{LSR}} \sim 27\text{--}36 \text{ km s}^{-1}$ may be spatially correlated with W50. On the other hand, Band et al. (1987) note that these clouds are located on the near side of and is not physically related with SS433. Subsequently, Durouchoux et al. (2000) suggest that CO clouds at $\sim 50 \text{ km s}^{-1}$ located towards the overlapped region of the West lobe of the X-ray jet may be interacting with the jet, because the X-ray hot spots are associated with them. Fuchs et al. (2002) observed the region with ISO and the IRAM 30m telescope to find that some of the IRAS knots are associated with these molecular clouds. One of these knots coincides with that noted by Durouchoux et al. (2000). Lockman et al. (2007) also studied the association between the SS433-W50 and CO clouds using FCRAO 14m telescope at $2 \text{ degrees} \times 2 \text{ degrees}$ centered on SS433. They concluded that there are no association between the SS433-W50 and the CO clouds.

To summarize, the previous works on the possible interaction between relativistic jet and the interstellar matter have shown the two possible cases of such interaction, SS433 and GRS1915+105. It is therefore still the beginning of observations of such interactions and theoretical studies of the interactions largely remain unexplored.

NANTEN, a 4m mm/sub-mm telescope located in Chile, has been used to make an extensive survey of the Galactic plane in ^{12}CO ($J=1\text{--}0$) emission at a grid spacing of $4'$ at $|b| \leq 5^\circ$ and that of $8'$ at $5^\circ \leq |b| \leq 10^\circ$ (for more details see e.g., Mizuno & Fukui 2004). This offers a few times spatially finer CO images at $|b| \leq 5^\circ$ compared to the previous low resolution CO survey (Dame, Hartmann & Thaddeus 2001). The new NANTEN CO dataset is useful to search uniformly for various phenomena towards $\pm 10^\circ$ of the Galactic plane on a large scale including supershells and other active events (e.g., Fukui et al. 1999, 2006; Matsunaga et al. 2001).

In the present paper, we show and discuss the observational results of molecular clouds which may be associated with relativistic jet toward SS433 and $l \sim 348.5^\circ$, and their implications. Section 2 gives a summary of the CO dataset. Sections 3 and 4 present the main observational results for the two regions and a model is presented and discussed in section 5. Conclusions are given in section 6.

2. The NANTEN CO Dataset

We used the NANTEN Galactic Plane Survey dataset of the ^{12}CO ($J=1-0$) emission (Mizuno & Fukui 2004). The coverage of the data is 220 degrees in l from $l \sim 200^\circ$ to 60° including the Galactic center and at $|b| \leq 5^\circ$ with a grid spacing of $4'$ and at $5^\circ \leq |b| \leq 10^\circ$ with a grid spacing of $8'$ for the main beam width of $2.6'$ in addition to the selected areas of nearby clouds at $|b| \geq 10^\circ$ (e.g., Mizuno et al. 2001; Onishi et al. 2001). The total number of observed points is ~ 1.1 million. The velocity coverage and resolution of the data are usually from 300 km s^{-1} to -300 km s^{-1} and 0.65 km s^{-1} , respectively. All the observations were carried out by the position switching technique. The telescope was equipped with a superconducting mixer receiver (Ogawa et al 1990). The system temperature including the atmosphere was in a range of 250–350 K in the single side band mode (=SSB) on average towards the zenith and the typical r.m.s. noise fluctuations of the spectral data are $\sim 0.35 \text{ K}/(0.65 \text{ km s}^{-1})$ in the absolute antenna temperature, T_{R}^* , corresponding to an integration time of a few to several seconds per point at on-position.

3. SS433

3.1. Large Scale Distribution of Molecular Clouds

Figure 1 shows the $^{12}\text{CO}(J=1-0)$ integrated intensity distribution whose velocity range is $V_{\text{LSR}} = 40$ to 60 km s^{-1} in the region of $l = 37^\circ$ to 42° and $b = -5^\circ$ to 0° . Superposed are the H I integrated intensity distribution at a 16 arcmin effective resolution with the Parkes 64m telescope (McClure-Griffiths et al. 2005) and ASCA X-ray distribution of the GIS image in the 0.7–10 keV band (Kotani 1998). We have identified ten ^{12}CO clouds along the X-ray jet axis of SS433 at the lowest 3σ contour level in $l \sim 39^\circ - 41.5^\circ$ and $b \sim -5^\circ - -1^\circ$. In the southeast of SS433 there are six clouds as named from SS433-S1 to SS433-S6 at $b \sim -3^\circ - -5^\circ$ and at $V_{\text{LSR}} \sim 42 - 45 \text{ km s}^{-1}$. In the northwest of SS433 there are four clouds as named from SS433-N1 to SS433-N4 at $b \sim -1^\circ - -2^\circ$ and at $V_{\text{LSR}} = 50 - 55 \text{ km s}^{-1}$. The observed parameters of these clouds are listed in Table 1.

These ten clouds exhibit a remarkably straight distribution along the axis of the X-ray jet of SS433. This alignment is approximated by a dashed line in Figure 1 as determined by a linear regression fit on the clouds weighted in the total CO intensity and is expressed as $b(^{\circ}) = (63 \pm 2)^{\circ} - (1.65 \pm 0.05) \times l(^{\circ})$ with a high correlation coefficient of ~ 0.98 . This line passes almost exactly through the position of SS433 (l, b) = $(39.7^\circ, -2.2^\circ)$ as shown in Figure 1. We note that the position angle of the line is $\sim 30^\circ$ in the galactic coordinate, while that of the X-ray jet is $\sim 20^\circ$, showing a small difference of $\sim 10^\circ$.

The southern clouds have been discovered by the present work. Some of the northern clouds have already been observed and the interaction with the SS433 jet has been discussed for SS433-N1 to SS433-N4 by the previous authors (Band et al. 1989; Durouchoux et al. 2000; Fuchs et al. 2002; Chaty et al. 2001; Moldowan et al. 2005).

Figure 2(b) shows the velocity distribution of the ^{12}CO clouds in a position-velocity diagram

superposed on the HI distribution. The position is the offset from SS433 taken along a line tilted to the galactic plane by 45° as indicated in Figure 2(a). Some of the clouds are overlapped in the figure and the number of the clouds apparently becomes less than ten. The typical velocities of the northern clouds, SS433-N1 to SS433-N4, and the southern clouds, SS433-S1 to SS433-S6, are $\sim 53 \text{ km s}^{-1}$ and $\sim 43 \text{ km s}^{-1}$, respectively, on average. We note that the internal velocity dispersions of these clouds are as small as 2 km s^{-1} while that of SS433-S6 is $\sim 4 \text{ km s}^{-1}$. It is not certain if another cloud at the offset of 1.5 and $V_{\text{LSR}} \sim 50 \text{ km s}^{-1}$ is related to the present northern clouds.

Figure 3 shows a larger scale view of the region in the ^{12}CO integrated intensity distribution in the same velocity range as in Figure 1, covering 50 square degrees from $l = 35^\circ$ to 45° and $b = -5^\circ$ to 0° . This demonstrates that there are only a few CO clouds except for the present ones over a volume of $\sim 500 \text{ pc}$ (in l) $\times \sim 100 \text{ pc}$ (in b) $\times \sim 1 \text{ kpc}$ in the line of sight (in v) at $b \lesssim -3^\circ$ for an assumed distance of $\sim 3 \text{ kpc}$ (see section 3.2). We note that the present CO southern clouds are distributed up to $z \sim 240 \text{ pc}$, very far out from the galactic plane whose typical scale height in the CO emission is $\sim 87 \text{ pc}$ (Dame et al. 1987). The southern CO clouds located at around -4° are therefore very rare and a group of such aligned clouds is quite unique. We shall hereafter assume that the ten clouds are at the distance of SS433 because of their similar velocities and alignment.

3.2. Physical parameters

The two average velocities of the CO clouds, 53 km s^{-1} and 43 km s^{-1} , correspond to kinematic distances of 3.5 kpc and 3 kpc , respectively, for the flat rotation curve (Brand & Blitz 1993) while another kinematic distance around $\sim 10 \text{ kpc}$ is also permitted. According to the previous studies, the distance to SS433 is estimated to be $\sim 3 \text{ kpc}$ from the absorption of atomic hydrogen (Gorkom, Goss, Shaver 1980) and the velocity of the cavity of atomic hydrogen (Dubner et al. 1998), $\sim 4.85 \text{ kpc}$ from six radio continuum images at two day intervals with VLBI by Vermeulen et al. (1993) and $\sim 5.5 \text{ kpc}$ from the radio continuum observations in the central part of SS433 with VLA (Hjellming & Johnston 1980, Blundell & Bowler 2004). We shall hereafter tentatively adopt the distance to SS433 the smaller value, 3 kpc , which is consistent with the present kinematic distance. This gives conservative estimates of related physical parameters such as the radius and mass of the molecular clouds. If the cloud velocity is affected by motion other than the galactic rotation, this estimate needs to be reconsidered.

The physical parameters of the clouds are calculated as listed in Table 2. We adopt the X factor, which is defined as $N(\text{H}_2)/W(^{12}\text{CO})$, of $2.0 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$ (Lebrum et al. 1983; Bertsch et al. 1993), in these calculations. The linewidth, mass, size, and peak T_{R}^* are similar to those of nearby dark clouds (e.g., Mizuno et al. 2001; Tachihara et al. 2001). The cloud mass ranges from $\sim 10^2$ to $\sim 10^3 M_\odot$. The total molecular mass of the southern clouds amounts to $\sim 5.9 \times 10^3 M_\odot$ while that of the northern clouds $\sim 9.0 \times 10^3 M_\odot$. The virial mass of these molecular clouds is several times larger than this luminous mass, indicating that the molecular clouds are not gravitationally bound; this is a typical property of molecular clouds in such a low mass range (e.g., Onishi et al. 2001; Yamamoto et

al. 2003, 2006). They may be confined by the ambient pressure or be transient at a timescale of $\sim 10^6$ yrs, the crossing timescale as discussed in the previous works including the above two.

3.3. Comparison with radio continuum, HI and X-ray around SS433

Figure 4 shows an overlay of the radio continuum distribution of W50, a supernova remnant associated with SS433, at 4850 MHz (e.g., Condon et al. 1989) on the HI 21 cm line integrated intensity in the V_{LSR} range 40 – 60 km s $^{-1}$. The SNR is elongated by $\sim 2^\circ$ towards the same direction as the X-ray jet while the width is $\sim 1^\circ$, significantly larger than the X ray, showing a sharp intensity gradient towards the galactic plane. The northern clouds SS433-N1, SS433-N2 and SS433-N3 are located towards the northern edge of the SNR and SS433-N4 seems to be located inside of the SNR. On the other hand, the southern clouds are separated from the SNR. Dubner et al. (1998) show that the SNR W50 is located towards a hole of the HI emission and argue that the hole may have been created by the supernova explosion. We confirm this suggestion as the HI depression towards SS433 in Figure 4. Recent HI study in and around the SS433-W50 reported by Lockman et al. (2007) suggests that the HI gas at a velocity ~ 75 km s $^{-1}$ has interacted with the W50 from the morphology of the HI gas by new observations and its distance. The 75 km s $^{-1}$ component of the HI gas also looks like interacting with SS433-W50 at upper part of the W50. But here we use the HI data at $V_{\text{LSR}} \sim 40\text{--}60$ km s $^{-1}$ because the velocity of present molecular clouds is $\sim 40\text{--}60$ km s $^{-1}$ and these are not associated with the HI at $V_{\text{LSR}} \sim 75$ km s $^{-1}$.

We find in Figures 1 and 3 that the southern CO clouds are located towards a HI protrusion peaked at $(l, b) \sim (40.9^\circ, -3.9^\circ)$, where the present CO clouds are distributed within a HI contour of 410 K km s $^{-1}$. Figure 2(b) shows that the CO velocity agrees with the HI velocity at the offset of -1° – -3° . These suggest that the southern CO clouds and the HI are physically associated. In Figure 2(b) the northern clouds also seem to be associated with the HI at the offset of 0.5° – 1° , while the HI velocity is slightly larger by a few km s $^{-1}$ than the CO velocity.

The HI mass of the protrusion towards $39^\circ \leq l \leq 41.4^\circ$ and $-3.4^\circ \leq b \leq -5^\circ$ within a contour level of 410 K km s $^{-1}$ is estimated to be $51000 M_\odot$ by using the conventional factor of the HI intensity into mass, 1.8×10^{18} cm $^{-2}$ /(K km s $^{-1}$). The total molecular mass of the southern CO clouds is $\sim 5900 M_\odot$, corresponding to about one tenth of that of HI.

ASCA X-ray distribution shown in Figure 1 indicates clearly the two lobes of the X-ray jet, the West and East lobes, respectively. SS433-N4 is located towards the West lobe and SS433-N1 and SS433-N3 show some overlapping with this lobe also. This may suggest some interaction between them as already noted by Durouchoux et al. (2000). SS433-N2 is somewhat far from the other clouds and its physical association with the X-ray lobe may not be certain. We note that the field of view of the X-ray observations towards the lobe is limited to the three fields centered on SS433 covering regions within $\sim 1^\circ$ of SS433. So, the distribution of the X-ray outside the area remains to be uncovered.

4. Linearly Aligned Molecular Clouds Perpendicular to the Galactic Plane towards $l \sim 348.5$

4.1. Large Scale Molecular Distribution

In the course of a detailed analysis of the ^{12}CO dataset, we have discovered an unusual aligned distribution of CO clouds toward $l \sim 348.5$. Figure 5 shows an integrated intensity distribution of ^{12}CO ($J=1-0$) emission whose velocity range is from $V_{\text{LSR}} = -100$ to -70 km s^{-1} in the region of $347^\circ \leq l \leq 350^\circ$ and $-3^\circ \leq b \leq 3^\circ$. Four clumpy clouds located at $b \sim 1.7, -0.8, -1.7$, and -2.1 are aligned nearly perpendicular to the Galactic plane where most of the intense CO emission is confined at $|b| \lesssim 0.5$. We shall tentatively assume the physical association of the four clouds in the following and name the group of the southern and northern clouds as MJG348.5 (=molecular jet at $l = 348.5$). We call hereafter the four components, MJG348.5-N, MJG348.5-S1, MJG348.5-S2, and MJG348.5-S3, respectively, as labeled in Figure 5. We note the separations between the northern and southern tips of the molecular clouds, MJG348.5-N and MJG348.5-S3, and the Galactic plane is nearly $\sim 2^\circ$, respectively. A linear regression fit to the four clouds, shown in Figure 5 by a dashed line, with integrated intensity weighting yields a relationship, $b(^{\circ}) = (-13.67 \pm 1.63) \times l(^{\circ}) + (4765.69 \pm 566.64)(^{\circ})$ with a correlation coefficient of ~ 0.89 , which passes through the Galactic plane at $l = 348.52$ and is nearly perpendicular to the Galactic plane at an angle between the line and the Galactic plane of $\sim 86^\circ$. The apparent largest separation of MJG348.5-S3 from the Galactic plane is ~ 2.4 . The V_{LSR} of the southern three components is $\sim -82 \text{ km s}^{-1}$ and that of the northern one is $\sim -95 \text{ km s}^{-1}$ as shown in Figure 6(a). We note that the two clouds, MJG348.5-N and MJG348.5-S3, exhibit the largest dispersion of $\sim 7 \text{ km s}^{-1}$ (see Figure 6(b) and (c)), while the other clouds, MJG348.5-S1 and MJG348.5-S2, show smaller velocity dispersions of $\sim 3 \text{ km s}^{-1}$.

We further note that another cloud is located at $l \sim 347.7$ and $b \sim 1.6$ at a LSR velocity of $\sim -83.0 \text{ km s}^{-1}$. This cloud is also unusual at such high latitude and large LSR velocity. We come back to this feature later in comparison with the HI and in the discussion section.

Figure 7 shows a larger scale view of the region in the ^{12}CO integrated intensity distribution in the same velocity range as in Figure 5, covering 200 square degrees from $l = 339^\circ$ to 359° and $b = -5^\circ$ to 5° . This demonstrates that there are only a few CO clouds except for the present ones over a volume of $\sim 2 \text{ kpc}$ (in l) $\times \sim 0.4 \text{ kpc}$ (in b) $\times \sim 0.9 \text{ kpc}$ in the line of sight (in v) at $|b| \leq 3^\circ$ for the kinematic distance of $\sim 6 \text{ kpc}$ as derived below. The CO clouds located at more than ± 1.5 in Galactic latitude are very rare and a group of such clouds aligned in a straight line is unique as in case of SS433. We shall further note that the present CO clouds are distributed to $z \sim 240 \text{ pc}$, very far out of the typical CO scale height of the CO emission, $\sim 87 \text{ pc}$ (Dame et al. 1987).

4.2. Physical Properties of the Molecular Clouds

The averaged V_{LSR} of the MJG348.5-S1, MJG348.5-S2, and MJG348.5-S3 is $\sim -82 \text{ km s}^{-1}$, corresponding to a kinematic distance of 5.9 kpc or 10.8 kpc, and that of MJG348.5-N of $\sim -95 \text{ km s}^{-1}$ corresponds to 6.1 kpc or 10.5 kpc, respectively, if we assume the flat rotation curve (Brand &

Blitz 1993). We shall tentatively adopt the smaller averaged value, ~ 6 kpc, hereafter, since it gives conservative estimates of the cloud parameters, noting that the kinematic distance may include a large uncertainty toward this direction near the center. For instance, the kinematic distance changes from 5.7 kpc to 6.0 kpc for a velocity difference of $+5 \text{ km s}^{-1}$, typical velocity dispersion in the HI clouds. The alignment of the three southern molecular clouds is remarkably good over a length of ~ 200 pc with a width of ~ 10 pc at 6 kpc. The location of the northern cloud, MJG348.5-N, is fairly symmetric to MJG348.5-S3 with respect to the plane.

The relevant observed and derived physical parameters of the present clouds are summarized in Table 3. The peak temperature and line width of the ^{12}CO emission of the four molecular clouds are 1.6 to 3.3 K and 3.3 to 5.4 km s^{-1} , not much different from those of the typical CO clouds whose average density and kinetic temperature are $n(\text{H}_2) \sim 10^2 \text{ cm}^{-3}$ and $T_k \sim 10$ K (see for typical nearby dark clouds, e.g., Mizuno et al. 2001; Tachihara et al. 2001). The range of mass of each CO cloud is from $\sim 1.5 \times 10^3$ to $\sim 1.4 \times 10^4 M_\odot$ by adopting X factor $N(\text{H}_2)/W(^{12}\text{CO})$, of $2.0 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$ (Bertsch et al. 1993). In total, the molecular mass in the four clouds is estimated to be $\sim 2.6 \times 10^4 M_\odot$. They share similar dynamical properties with those in SS433 as mentioned in Section 3.2.

4.3. Comparison with the HI

Figures 8(a) and (b) show two velocity channel maps of ^{12}CO superposed on the distribution of the 21 cm HI line emission integrated in the corresponding velocity ranges. The effective HI resolution is 16 arcmin with the Parkes 64m telescope (McClure-Griffiths et al. 2005). The strong HI emission at $|b| \lesssim 1^\circ$ is the Galactic disk emission. At $|b| \gtrsim 1^\circ$ we are able to identify the HI features associated with the present CO clouds. Towards MJG348.5-N at $b \sim 1.7^\circ$, an isolated HI cloud is found in Figure 8(a). This HI cloud having a size of $\sim 50 \text{ pc} \times \sim 30 \text{ pc}$ at 60 K km s^{-1} is elongated in a similar direction to the CO distribution from NW to SE tilted to the Galactic plane by ~ 45 degrees. Towards the southern three clouds, MJG348.5-S1, MJG348.5-S2, and MJG348.5-S3, we see that a protrusion of the HI emission is extended at $l \sim 348.5^\circ$ up to $b \sim -2.4^\circ$. MJG348.5-S2 is associated with part of the HI protrusion towards $l \sim 348.6^\circ$ and $b \sim -1.7^\circ$ at a contour level of $\sim 135 \text{ K km s}^{-1}$. This HI emission has a size of $\sim 100 \text{ pc} \times \sim 60 \text{ pc}$ at the HI contour level of 105 K km s^{-1} elongated to the Galactic plane by ~ 45 degrees from NE to SW. The HI protrusion is also identified in Figure 6(a) in a velocity range from -90 km s^{-1} to -75 km s^{-1} at the HI contour level of $\sim 85 \text{ K degree}$. In addition, MJG348.5-S3 is associated with the southern extension of the HI protrusion towards $l \sim 348.6^\circ$ and $b \sim -2.0^\circ$ (Figure 8(b)), which is identified at $V_{\text{LSR}} \sim -80 \text{ km s}^{-1}$ in Figure 6(a). These spatial and velocity extents of the HI emission is to be regarded as the lower limits by considering the possible more extended HI features at lower intensity levels.

We have further inspected the HI distribution in detail. Figure 9 shows the longitude-velocity diagrams of the HI superposed on the CO in b from 2.53 to -2.53 except for the area within ± 0.53 degrees where contamination is strong. The CO emission is clearly associated with HI at panels (d),

(e), (l), (p), (q), (r), and (s) in Figure 9, confirming that the H I is associated with MJG348.5-S3. The H I associated with MJG348.5-S3 is not clearly resolved but the upper limits of the line width and the radius of the H I associated with MJG348.5-S3 are roughly estimated to be $\sim 5 \text{ km s}^{-1}$ and $\sim 6.8 \text{ arcmin} = 12 \text{ pc}$ at 6 kpc, respectively, yielding the crossing time of the H I, $\sim 2.3 \times 10^6 \text{ yrs}$, similar to that of the molecular cloud, MJG348.5-S3. The mass of the associated H I both in the southern protrusion and in the northern cloud is estimated to be $\gtrsim 25000 M_{\odot}$ at an H I integrated intensity level of 100 K km s^{-1} , which is about two thirds of the total mass of the four molecular clouds. Here, we used the conventional relationship to convert the H I intensity into mass $1.8 \times 10^{18} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ by assuming optically thin H I emission.

We shall note that the CO cloud towards $l \sim 347^{\circ}.7$ and $b \sim 1^{\circ}.6$ at a LSR velocity of -83.0 km s^{-1} show H I counterpart. This cloud is clearly associated with H I as seen in panel (e) and (f) of Figure 9. Figure 8 also shows this H I cloud in panel (b). We further note that an H I protrusion is seen towards $(l, b) = (347^{\circ}.5, -1^{\circ}.4)$ of Figure 8 which could be a possible counterpart in the south. The real physical association of these clouds are yet uncertain compared with MJG348.5 clouds.

To summarize, the H I distribution superposed in the position-velocity diagrams (Figures 6(a) and 9) and in the sky (Figure 8(a) and (b)) suggest that H I gas is physically associated with the four molecular clouds.

4.4. High Energy Objects in the Galactic Plane

Energetic sources are not associated towards the individual molecular clouds but toward the Galactic plane at $l \sim 348^{\circ}.5$, the point of crossover between the straight line defined by these molecular clouds (Section 4.1) and the Galactic plane, there are several energetic sources already confirmed by observations of non-thermal radio emission, X-rays and γ -rays as summarized in Table 4. In Figure 5, the positions of the known supernova remnants, SNR G348.5+0.1 (CTB37A), G348.5-0.0, and G348.7+0.3 (CTB37B) are shown by crosses (e.g., Kassim et al. 1991). In addition, there are two TeV γ -ray sources confirmed by H.E.S.S. observations which may be associated with these SNRs or their stellar remnants as shown in Figure 15 of Aharonian et al. (2006). We note that the positional coincidence of the crossover point and these energetic sources, in particular CTB37A, is remarkably good. Other high energy sources are identified by EGRET and ROSAT All Sky Survey (Hartman et al. 1999; Voges et al. 1999) near the three SNRs although positions between these sources and the three SNRs are slightly different except for 1RXS J171354.4-381740 as shown in Figure 5 (see also Table 2). The relationship between molecular clouds and these energetic sources will be discussed in the next section.

5. Discussion

5.1. The Aligned Molecular Clouds

The present study has revealed remarkably well aligned molecular clouds of $\sim 300\text{--}400 \text{ pc}$ in length in the two fields of the Galaxy. The existence of the CO clouds itself is rare at high z

greater than ~ 100 pc. The alignments are not accidental by considering the even rare coincidence in velocity; the several clouds on a line passing through SS433 at $z \sim 200$ pc strongly indicate the physical association among them and also with SS433. The similar features in MJG348.5 are also very unusual, suggesting their physical association. The probability for such aligned clouds is indeed very low as shown in Appendix.

We shall here estimate the spatial and velocity dispersions of the aligned molecular clouds. In SS433, only the southern clouds are dealt with because the northern clouds are contaminated by the galactic background emission. The 1σ dispersion of the displacement of the molecular clouds from the dashed line in Figure 1 is around $\sim 9.7 \pm 2.0$ pc for the intensity-weighted average. Figure 2(b) was used to estimate 1σ velocity dispersion as $\sim 5.0 \pm 1.0$ km s $^{-1}$. The same procedure was applied to the MJG348.5 clouds, yielding spatial dispersion of $\sim 7.3 \pm 1.4$ pc and velocity dispersion of $\sim 2.2 \pm 0.3$ km s $^{-1}$, respectively. These small dispersions in the both cases indicate the excellent alignments both in space and velocity (Table 1).

SS433 is one of the best-studied compact objects driving relativistic jet. The jet of SS433 has a spatial extent of ~ 80 pc in the X-ray, the largest size of such jet known to date in the Galaxy. The jet is still being accelerated near the driving source at a velocity of $0.26c$ as determined from the Doppler measurements of H α emission (Margon et al. 1979). The jet is likely driven by the accretion disk plus a stellar remnant which has a deep gravitational potential well of a black hole or a neutron star. The disk material is perhaps being supplied from a counterpart of the binary, an ordinary evolved star having a large envelope. On the other hand, MJG348.5 does not have a known jet-accelerating object in the center. We shall first focus on SS433 in the following and discuss a possibility that the present clouds were created by the relativistic jet driven by a compact object and then we shall extend the model to MJG348.5.

Before moving to the relativistic-jet interpretation, we shall consider two alternative possibilities, i.e., "protostellar bipolar outflow" and "supershell wall" to explain the aligned clouds. The known molecular outflow from young stars is several pc at most in length, nearly two orders of magnitude smaller than in the present two cases of SS433 and MJG348.5 (e.g., Lada 1985; Fukui 1989; Bally et al. 2005), and exhibits the broad linewidths in the order of 10–100 km s $^{-1}$, more than an order of magnitude larger than the present linewidths. The aligned clouds are therefore quite different from the protostellar outflow. Supershells produced by massive stars via supernovae and/or stellar winds may offer an explanation for the high z distribution and the large extents of ~ 100 pc. The known molecular supershells are indeed characterized by a few 100 pc radius (Fukui et al. 1999; Yamaguchi et al. 1999; Matsunaga et al. 2001) but the straight distribution of the present clouds are hard to be reconciled with part of an expanding shell which should show non-uniform curved patterns in space and velocity typical to shells. We shall not discuss further on the supershell interpretation.

5.2. *The relativistic-jet model*

5.2.1. *Scenario*

The origin of the molecular clouds towards the SS433 region is explained as follows. Relativistic jet whose expanding velocity is a few tens % of the light speed, part of which is observed as the X-ray jet, interacted with the H I gas peaked towards $(l, b) = (40^\circ.9, -3^\circ.9)$. The interaction with the jet agitated the pre-existent H I gas dynamically and heated it up significantly. The kinetic power of the SS433 jet $\sim 1.1 \times 10^{46}$ erg/yr is in fact huge (Table 3); we shall tentatively assume that very hot gas such as observed in the X-ray jet is created via the interaction since any detailed calculations on the process are not found in the literature. A natural consequence of the interaction is a cylindrical expanding shock front compressing the gas, which leads to formation of the molecular clouds around the jet axis. The measured velocity and spatial dispersions of the clouds in Table 1 indicate that the typical expansion velocity and radius of the expanded cylinder are $2\text{--}5 \text{ km s}^{-1}$ and $7\text{--}10 \text{ pc}$, respectively. The timescale is then estimated roughly to be a few Myr by dividing the radius with the velocity. This offers an explanation on the straight distribution of the present southern CO clouds. The spatial coincidence of the southern CO clouds with the H I protrusion over a length of $\sim 60 \text{ pc}$ is consistent with this scenario because the background atomic gas is the necessary condition to form molecular clouds. The observed clumped CO distribution may be due to the initial density inhomogeneities in H I, which is not yet resolved with the present H I beam in Figure 1, or due to the gravitational instability in the shock-compressed H I gas. A similar process may have taken place in the north to form the northern clouds where the higher H I density near the galactic plane. The southern jet is extended at least $\sim 150 \text{ pc}$, while the northern jet can be traced up to $\sim 50 \text{ pc}$. This asymmetry may be ascribed to the increased deceleration near the galactic plane.

The length of the observed X-ray jet indicates that the jet has a momentum large enough to travel over at least $\sim 40 \text{ pc}$. The present scenario implies that the relativistic jet of SS433 has an actual full extent of $\sim 150 \text{ pc}$ on the southern side, significantly larger than the known size of the X-ray jet. We note that the X-ray observations by Kotani (1998) does not cover the area of the present southern clouds at b less than -2° and the X-ray observations yet remain to be extended towards the region of the southern clouds.

In order to explain the distribution of the aligned clouds toward $l \sim 348^\circ.5$, we argue that the same mechanism as in SS433 is working there by assuming the existence of relativistic jet and a compact driving engine similar to SS433. All the basic aspects of the interaction in SS433 are then applicable to MJG348.5. The background H I is also rich towards the CO clouds as is consistent with the model. The number of the clouds, four, in MJG348.5 is less than in SS433. This may be due to the lower spatial resolution at 6 kpc and/or due to the difference in the initial H I distribution.

5.2.2. *Timescales*

We may estimate the timescale of the interaction. An obvious one is the traveling time over $\sim 200 \text{ pc}$ as given by $\gtrsim (150\text{--}240 \text{ pc})/0.26c \sim 3 \times 10^3 \text{ yrs}$. More practical timescale of the interaction will be larger than this when we consider the concerned physical and chemical processes. A possible

preliminary guess on timescales is a crossing timescale of $\sim 10^6$ yrs for each CO cloud. This is roughly consistent with that from the ratio of the velocity and spatial dispersions of the clouds along the jet axis although the estimates should be crude at best and much affected by the initial conditions in the width of the relativistic jet and fluctuations of the HI gas in velocity and density. For instance, the jet may expand in width at 100–200 pc from the engine, causing the increase of the molecular-jet width. In such a case the timescale should be smaller than the above.

Another possible constraint is the timescale for CO formation in the HI gas via interstellar shocks, which requires $\sim 10^5$ – 10^6 yrs depending on density. Recent studies of high latitude molecular clouds associated with a shell created by stellar wind offer an observational support for molecular formation by the shock compression (Yamamoto et al. 2003, 2006). A theoretical study shows that the shock-produced CO clouds should have peak velocities and velocity dispersions similar to those of the ambient HI gas (see Koyama & Inutsuka 2002). The observed velocity dispersion among the CO clouds, ~ 2 – 5 km s^{-1} , seems consistent with this. In order to obtain a more detailed understanding of the physical processes in the interaction, we definitely need to elaborate on the physical and chemical processes in the shock which is beyond the scope of this paper. Theoretical studies of magneto-hydrodynamics of such interaction have been made for protostellar jet (Shibata & Uchida 1990) and are to be extended to the relativistic jet with appropriate modifications of physical parameters. Such studies will shed more light on the processes discussed above.

Another issue to be considered in SS433 is the timescale of the SNR. The lifetime of W50 is generally assumed to be an order of 10^4 yrs (Safi-Harb & Ogelman 1997; Safi-Harb & Petre 1999) but the present model suggests that the lifetime of the SS433 jet may be an order of magnitude larger than the assumed lifetime of the SNR. It is important to reinvestigate a possible range of the timescale of the SNR allowed under the present observed physical parameters.

5.2.3. *Energetics*

We shall examine the energy balance in the interaction by focusing on the SS433 southern clouds where the interaction is more clearly identified than in the north. In Table 3, the kinetic power of the southern SS433 jet is estimated to be $\sim 1 \times 10^{46} \text{ erg yr}^{-1}$ for the speed and mass flow rate derived from the H α emission (Marshall et al. 2002). The energy deposit in the molecular gas through the interaction is roughly estimated to be $\sim 10^{48} \text{ erg}$ for an assumed expansion velocity of $\sim 5 \text{ km s}^{-1}$, the velocity dispersion among the CO clouds (Table 1). This corresponds to 10^{-3} of the total energy of the jet if its duration of is $\sim 10^5$ yrs, suggesting that the energy requirement is well satisfied under the SS433 jet properties and that most of the deposited energy is radiated away. MJG348.5 also has similar expansion energy of the molecular clouds and is explicable with the parameters of the SS433 jet. If we take into account the atomic mass, this energy may become somewhat larger but not by more than an order of magnitude.

5.2.4. *The interaction with HI*

In the present scenario, the jet should lose its momentum through the interaction with the pre-existent HI gas. As long as the jet is running at a velocity close to the light speed, we expect the

alignment of the formed molecular clouds along the axis because the velocity of the jet is much faster than the local turbulent motion of several km s^{-1} in the undisturbed HI gas (see, e.g., Figures 2(b) and 6(a)). When the deceleration becomes significant so that the expanding speed becomes less than the local turbulent velocity of HI, the distribution of the forming clouds may become dominated by the local ambient velocity field. The large velocity dispersions are in fact seen only towards the tips of the jet, i.e., in SS433 south cloud (SS433-S6), MJG348.5-N and MJG348.5-S3, and the magnitude of the velocity dispersion, several km s^{-1} , is roughly consistent with the local turbulent motion of HI. These enhanced dispersions at the tips may indicate the deceleration at the end of the interaction.

In SS433, it is somewhat unusual that the HI gas is distributed at such high galactic latitude of $\sim -4^\circ$ prior to the interaction. We suggest that this may be due to the stellar winds by an early type star which caused supernova explosion prior to the formation of the relativistic jet. Such a gas shell is found in CO, HI and the dust emission in Pegasus loop which is driven by an early B-type star (Yamamoto et al. 2006). The HI gas in the south is perhaps part of the shell created by the stellar wind of the supernova precursor.

The mass of each molecular cloud formed by the interaction is an order of $10^2\text{--}10^3 M_\odot$ and is comparable to the mass of the HI gas in the cylinder of the length of 10 pc and radius of 10 pc which is typical size of molecular clouds having density of $\sim 10\text{--}30 \text{ cm}^{-3}$.

5.2.5. *Tilt of the jet*

It is suggested that the SS433 jet is tilted to the line of sight by 12 degrees in the sense that the southern part is closer to us (Hjellming & Johnston 1981). This is qualitatively consistent with that the southern clouds have smaller velocities than the northern clouds by $\sim 10 \text{ km s}^{-1}$, while the nominal difference ~ 500 pc between the northern and southern clouds in the kinematic distance seems too large, where the radial velocity is perhaps affected by the motion other than the galactic rotation like the expansion of the HI gas noted above. We should in addition recall that there is a small difference in the projected angle between the molecular jet and the X-ray jet by 10 degrees. This may be ascribed to a long-term precession of the axis, or alternatively, to the relative motion of the ambient HI gas.

In MJG348.5, the northern part has blue-shifted velocities compared to the southern part by $\sim 15 \text{ km s}^{-1}$. This is explicable as that the jet axis is somewhat tilted to the line of sight in the sense that the northern part is closer to us, while we should be cautious about the large uncertainties in the kinematic distance again.

5.2.6. *The candidates for the driving source in MJG348.5*

In SS433, the driving engine is most likely SS433 itself located at $(39^\circ 69', -2^\circ 24')$ in (l, b) . On the other hand, such a compact object are not uniquely identified in MJG348.5. There are some SNRs and X-ray/ γ -ray sources towards MJG348.5 in the literature (see section 4.2). We note that the distances to the three SNRs, CTB37A, CTB37B, and G348.5-0.0, are estimated by various methods to be ~ 3.1 kpc, ~ 4.8 kpc, and ~ 10 kpc, respectively (e.g., Caswell et al. 1975; Vermeulen et al. 1993; Reynoso & Mangum 2000). These values are different from the present kinematic distance, 6 kpc, although there is a large uncertainty in the kinematic distance towards the center of the Galaxy. It

should be important to make detailed observations of the energetic sources in the field at radio, X-ray and γ -ray wavelengths. The present scenario suggests that the interaction occurred $\gtrsim 10^5$ yrs ago, possibly longer than the timescale of the currently observed energetic objects mentioned above and it is also possible that the driving source of MJG348.5 is not active now. Based on these considerations, we shall postpone discussing the driving engine until more details of the high energy objects are revealed towards the center of MJG348.5.

5.3. *Further Implications*

The most developed jet in the Galaxy known to date is that in SS433 (e.g., Margon 1984; Margon & Anderson 1989; Kotani 1998). GRS1915+105 is another possible candidate if the association of the IRAS sources are correct (Chaty et al. 2001). Such an example showing an elongated jet of more than 10 pc in length is very rare except for SS433 and possibly GRS1915+105 in the Galaxy. Relativistic jets observed in the X-ray or radio synchrotron emission are usually much smaller in their size than the SS433 jet. These include pulsar wind nebulae (=PWN) like Crab and radio/X-ray jets including Cygnus X-1 (Gallo et al. 2005) and are in the order of several pc at most. The length of the jet and physical properties of molecular clouds between SS433 and MJG348.5 are nearly the same and the physical parameters of the driving source of MJG348.5 may be similar to those of SS433.

The present discoveries have shown the first candidates for the 400-pc-scale jet from a stellar remnant, three to five times longer than previously known in the Galaxy. It is also noteworthy that the relativistic jet may be able to interact with the interstellar medium to form molecular clouds. The present findings have opened a new possibility to use the millimeter CO emission to search for relativistic jet from a black hole or a neutron star. The time scale of the jet formation is $\sim 10^{5-6}$ yrs, offering a probe for a past episode of relativistic jet. At the moment we have only two cases of this kind of molecular jet. This is not surprising since the CO surveys with high angular resolutions has rarely been made for the latitude range above 1° in $|b|$ extensively (Jackson et al. 2006). High resolution CO surveys with a large latitude coverage has a potential to broaden our knowledge on black holes and neutron stars and their related activities in the Galaxy.

We recall the other unusual feature seen in Figure 5 towards $(l, b) \sim (347.7, 1.6)$ (section 4.1). This cloud may represent the third sample of this type; we shall note that there is a hint of an HI protrusion, a possible counterpart without CO, below the galactic plane at $b \sim -1^\circ$ at a similar longitude (see Figure 8, $(l, b) = (347.5 - 347.7, -1.5 - 1.5)$). We cannot exclude a possibility that this cloud is an object similar to MJG348.5 although the supportive evidence is yet weaker than in the other two at the moment.

The process in the present scenario is analogous to what is familiar as the "vapor trail" produced by a jet airplane in the Earth's atmosphere although the detailed mechanism of formation is obviously different; the vapor trail is solid or liquid water condensed under the influence of the hot ejected matter by a jet engine. A common phenomenological property between the present jet and the vapor trail is that the remnant trail survives over a much longer time scale than that of the interaction,

holding the position of the path of the interaction. We shall propose to call the present jet as "galactic vapor trail" because of such similarity.

6. Conclusions

Main conclusions of the present study are summarized as follows;

1. We have carried out a detailed analysis in two large areas of ~ 25 square degrees around SS433 and of ~ 18 square degrees towards $l \sim 348.5$ using the NANTEN Galactic Plane Survey $^{12}\text{CO}(J=1-0)$ dataset. We have discovered two groups of well aligned molecular clouds; ten molecular clouds along the X-ray jet axis of SS433 and four molecular clouds towards $l \sim 348.5$ over ~ 4 degrees in b with ~ 10 arcmin width perpendicular to the Galactic plane.
2. We suggest that the aligned molecular clouds in the SS433 region represent the molecular gas created by the interaction between the relativistic jet and the interstellar H I gas. The present clouds are extended by ~ 150 pc at a kinematic distance of 3 kpc, suggesting that the relativistic jet is more extended by a factor of about three towards the south than the X-ray jet.
3. We apply the same relativistic-jet model to the MJG348.5 clouds in order to explain the alignment over ~ 400 pc at a kinematic distance of ~ 5 kpc and suggest that the clouds were created by the interaction between the hypothetical relativistic jet and the H I gas. Four high energy objects, three SNRs and a gamma ray source, in the galactic plane are considered as the candidate for the driving engine while none of them has known relativistic jet at the moment.
4. In either case, the estimated kinetic energy of the molecular clouds is $\sim 10^{48}$ erg, corresponding to 1% of the total kinetic energy released in relativistic jet from SS433 over $\sim 10^5$ yrs. This suggests that the energy of the relativistic jet is large enough to form such molecular clouds.
5. We suggest that the present findings open a new possibility to search for candidates of a neutron star or a black hole over more than 10-times longer timescales than the direct detection of high energy radiation from these compact objects. We name the phenomenon as "galactic vapor trail" from the analogy with the vapor trail created by jet airplanes.

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Appendix. Probability of the aligned clouds

Here we shall give a quantitative estimate of the probability for an alignment of molecular clouds along a jet axis.

We shall first assume that a jet axis is defined by two clouds at lower latitude (e.g., MJG348.5) or by the driving engine and another cloud at lower latitude (e.g., SS433). We shall then estimate the probability to find another cloud at higher latitude on the jet axis including the agreement in velocity.

In case of MJG348.5, the jet axis is defined by MJG348.5-S1 and MJG348.5-S2, and MJG348.5-S3 "happens" to be located on the axis at higher latitude above 2 degrees. Figure 7 does illustrate that such a CO cloud like MJG348.5-S3 at above 2 degrees is only one in the field presented, very rare on both the negative and positive latitudes. The only one exception is seen at $(l, b) \sim (356^\circ, 2^\circ)$ which is the top of the proposed magnetic floatation loop further away in the galactic center (Fukui et al. 2006). We estimate that only one cloud, MJG348.5-S3, is found for an area of $500 \text{ pc} \times 500 \text{ pc}$ projected on the galactic plane (Figure 10(a)), where 500 pc corresponds to a half of the projected length along the longitude as well as along the line of sight estimated from the velocity span covered, from -100 km s^{-1} to -70 km s^{-1} , shown in Figure 7.

By adopting a typical cloud size 10 pc as a size of a 2 dimensional cell, we shall estimate the probability to find S3 on the jet axis as to be $10\text{pc}/500\text{pc} \times 10\text{pc}/500\text{pc} = 1/50 \times 1/50 \sim 4 \times 10^{-4}$. This is actually a secure upper limit since there is another cloud N on the positive latitude, whose alignment makes the probability of MJG348.5 even smaller.

In case of SS433, the jet axis is defined by two objects, SS433 itself and, for simplicity, a set of clouds SS433-S1–SS433-S4 at b below -4 degrees which has a typical spatial dispersion of 10 pc around the jet axis (Figure 10(b)). Another set of clouds, SS433-S5 and SS433-S6, then "happens" to be located on the axis at b above -4 degrees. Figure 3 does illustrate that such a set of CO clouds like SS433-S5 and SS433-S6 at above -4 degrees is only one in the field presented. We again estimate that a set of CO clouds is found for an area of $300 \text{ pc} \times 300 \text{ pc}$ projected on the galactic plane (Figure 10(b)), where 300 pc corresponds to a half of the along longitude projected on the sky as well as the depth along the line of sight estimated from the velocity span covered, from 40 km s^{-1} to 60 km s^{-1} , shown in Figure 3. By using the same argument as above, we estimate the probability to find the clouds on the jet axis to be $10\text{pc}/300\text{pc} \times 10\text{pc}/300\text{pc} = 1/30 \times 1/30 \sim 10^{-3}$.

To summarize, we argue that the probability of the present aligned clouds is as small as $10^{-3} - 3 \times 10^{-4}$.

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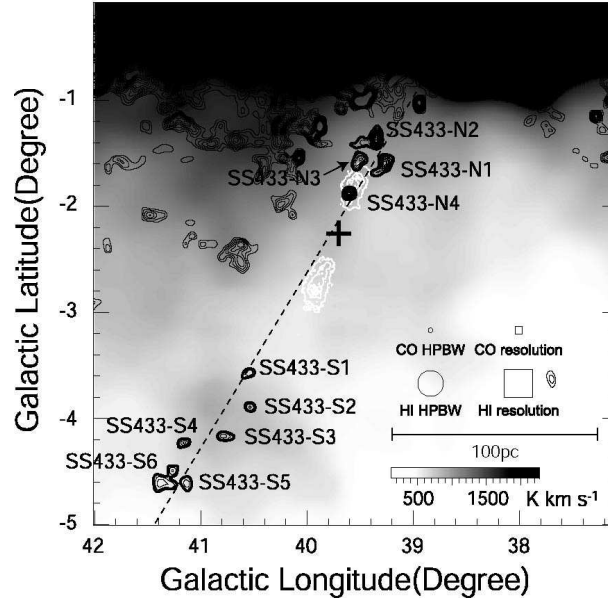


Fig. 1. The integrated intensity map of $^{12}\text{CO}(J=1-0)$ (black contours) superposed on the HI (gray scale) whose velocity range is 40 to 60 km s^{-1} . Boundaries of SS433-N1 – SS433-N4, and SS433-S1 – SS433-S6 are shown in thick contour lines. The contours of the CO are illustrated every 1.8 K km s^{-1} from 3.6 K km s^{-1} . The black cross indicates the position of SS433, and white contours indicate ASCA X-ray image of the SS433 lobes. The dashed line indicates the result of the linear regression fit to the north and south clouds.

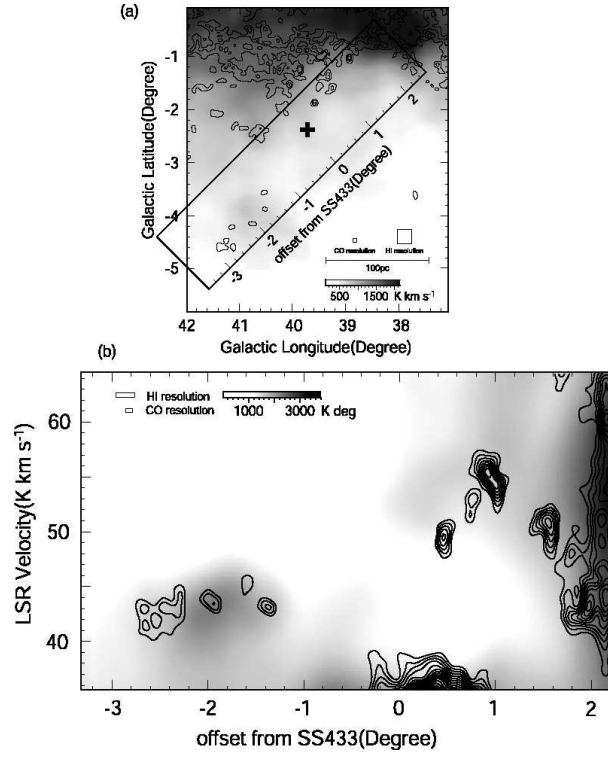


Fig. 2. (a) The same as Figure 1, but contour levels of CO are every 10 K km s^{-1} from 3.6 K km s^{-1} . (b) The position-velocity diagram of $^{12}\text{CO}(J=1-0)$ emission (contours) superposed on the H I (gray scale) which is integrated in direction of the long side of rectangle in (a). The contours of the CO are illustrated every 1.5 K deg from 5.5 K deg . Offsets are relative to the position of SS433.

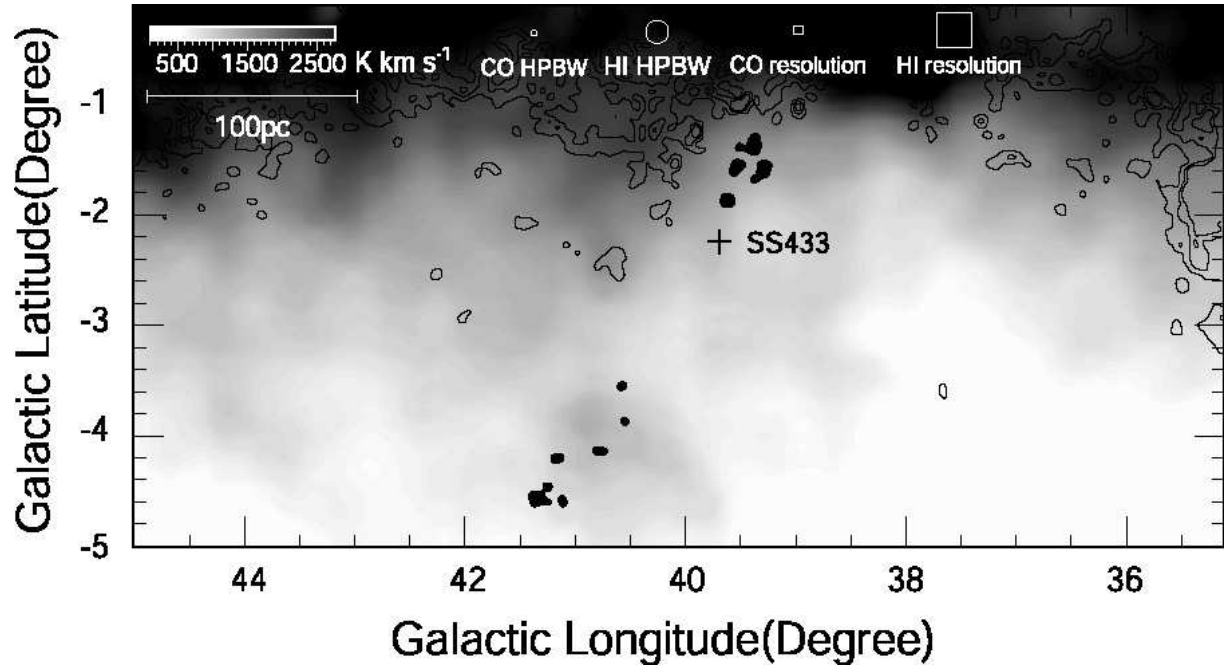


Fig. 3. The large scale integrated intensity map of $^{12}\text{CO}(J=1-0)$ (black contours) superposed on the HI (gray scale) whose velocity range is 40 to 60 km s^{-1} . The contours of the CO are illustrated every 10 K km s^{-1} from 5.8 K km s^{-1} . The black cross indicates the position of SS433. North and south clouds are filled in black.

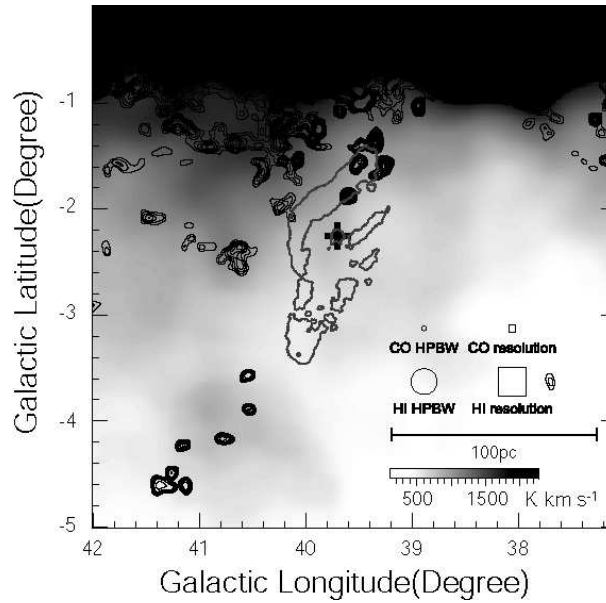


Fig. 4. The same as Figure 1, but VLA radio continuum image of W50 at 4850MHz is superposed instead of ASCA X-ray image.

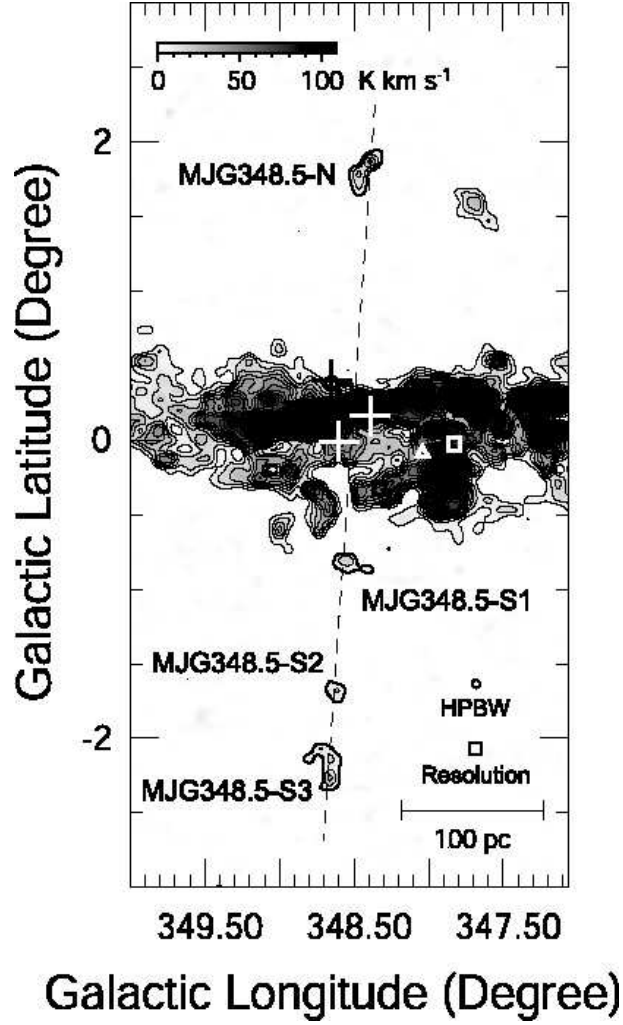


Fig. 5. The integrated intensity map of $^{12}\text{CO}(J=1-0)$ whose velocity range is -100 to -70 km s^{-1} . The contours of CO are illustrated every 4.2 K km s^{-1} from 4.2 K km s^{-1} (5σ). Four molecular clouds, MJG348.5-N, MJG348.5-S1, MJG348.5-S2, and MJG348.5-S3, are shown in the figure and boundaries of them are shown in thick contours. The crosses indicate the positions of the supernova remnants, CTB37A: $(l, b) \sim (348^\circ 39, 0^\circ 16)$, CTB37B: $(l, b) \sim (348^\circ 65, 0^\circ 40)$, and G348.5-0.0: $(l, b) \sim (348^\circ 60, -0^\circ 01)$. The circle and triangle indicate the positions of the γ -ray sources identified by H.E.S.S. and EGRET, respectively. The squares indicate the positions of X-ray sources identified by ROSAT. These symbols are illustrated by white and black in the region where the integrated intensity of CO is high and low, respectively. These source are listed in Table 2.

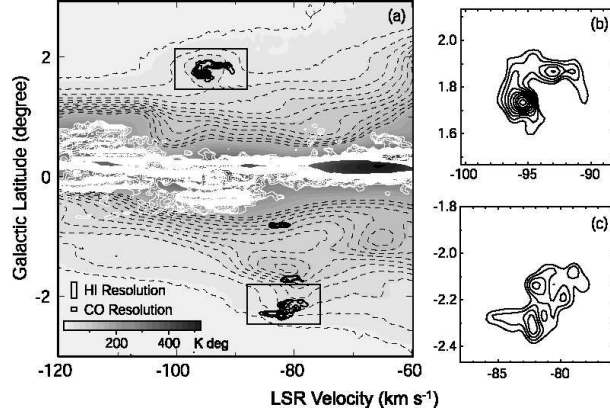


Fig. 6. (a) The velocity-latitude diagram of $^{12}\text{CO}(J=1-0)$ emission (black and white contours) superposed on the H I (gray scale and dotted contours) whose integrated range in the Galactic longitude is from $348.^\circ267$ to $348.^\circ800$. MJG348.5-N, MJG348.5-S1, MJG348.5-S2, and MJG348.5-S3 are shown in black solid contours. The contour levels of CO are shown up to 20 K deg every 0.6 K deg from 1.5 K deg and those of the H I up to 145.2 K deg every 12 K deg from 13.2 K deg. The resolution of CO and H I are shown in the figure. (b), (c) Close-up views of the upper and lower boxes in (a) for only ^{12}CO . The contour levels of ^{12}CO in (b) and (c) are the same as (a).

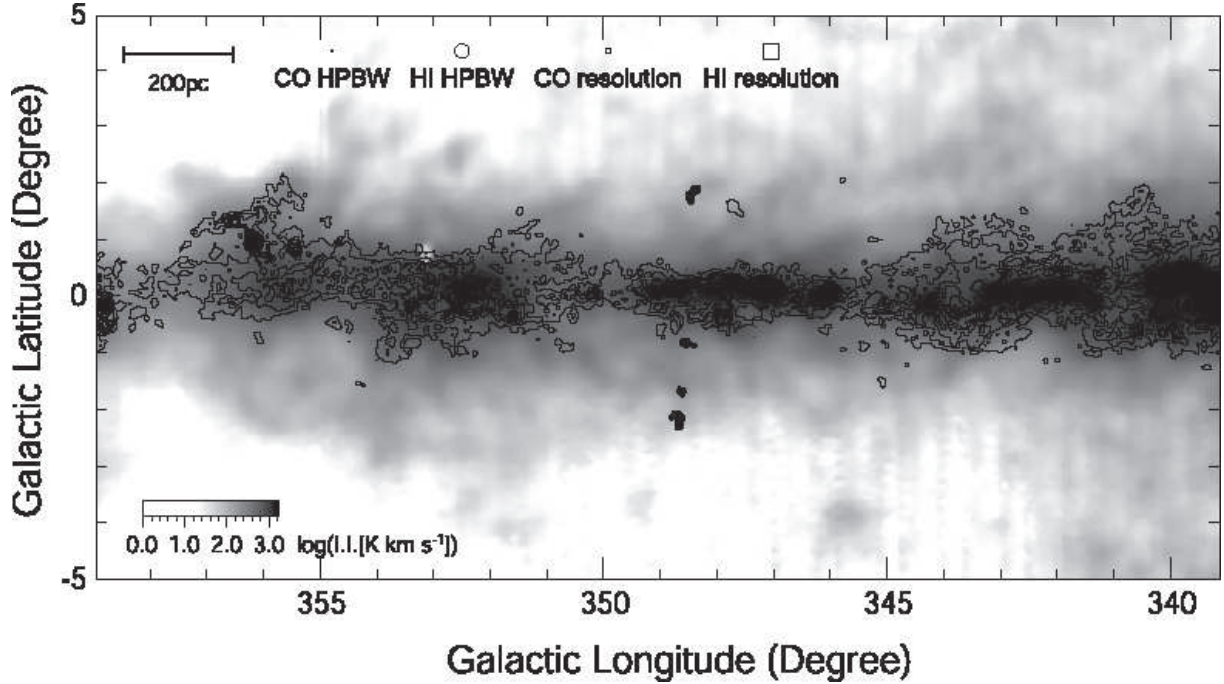


Fig. 7. The large scale integrated intensity map of $^{12}\text{CO}(J=1-0)$ (solid contours) superposed on H I (dashed contours and gray scale) whose velocity range is -100 to -70 km s^{-1} . The intensity of the CO is illustrated in linear scale and that of the H I is illustrated in logarithmic scale. The four molecular clouds, MJG348.5-N, MJG348.5-S1, MJG348.5-S2 and MJG348.5-S3 toward $l \sim 348.^\circ5$ are filled in black.

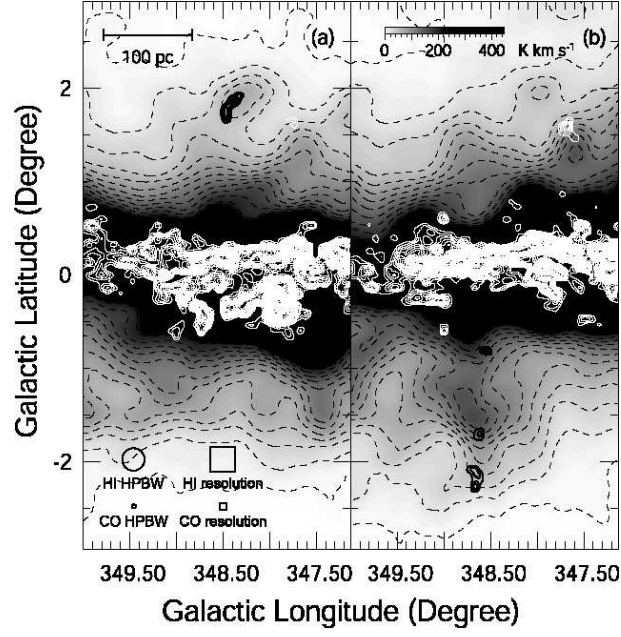


Fig. 8. The integrated intensity channel maps of $^{12}\text{CO}(J=1-0)$ (black and white contours) superposed on that of HI (gray scale and black dashed contours). MJG348.5-N, MJG348.5-S1, MJG348.5-S2 and MJG348.5-S3 are shown in black solid contours. The velocity ranges of both CO and HI data in (a) and (b) are -100 to -85 km s^{-1} and -85 to -70 km s^{-1} , respectively. The contours of CO and HI are illustrated every 2.1 K km s^{-1} from 4.2 K km s^{-1} and every 15 K km s^{-1} from 15 K km s^{-1} , respectively.

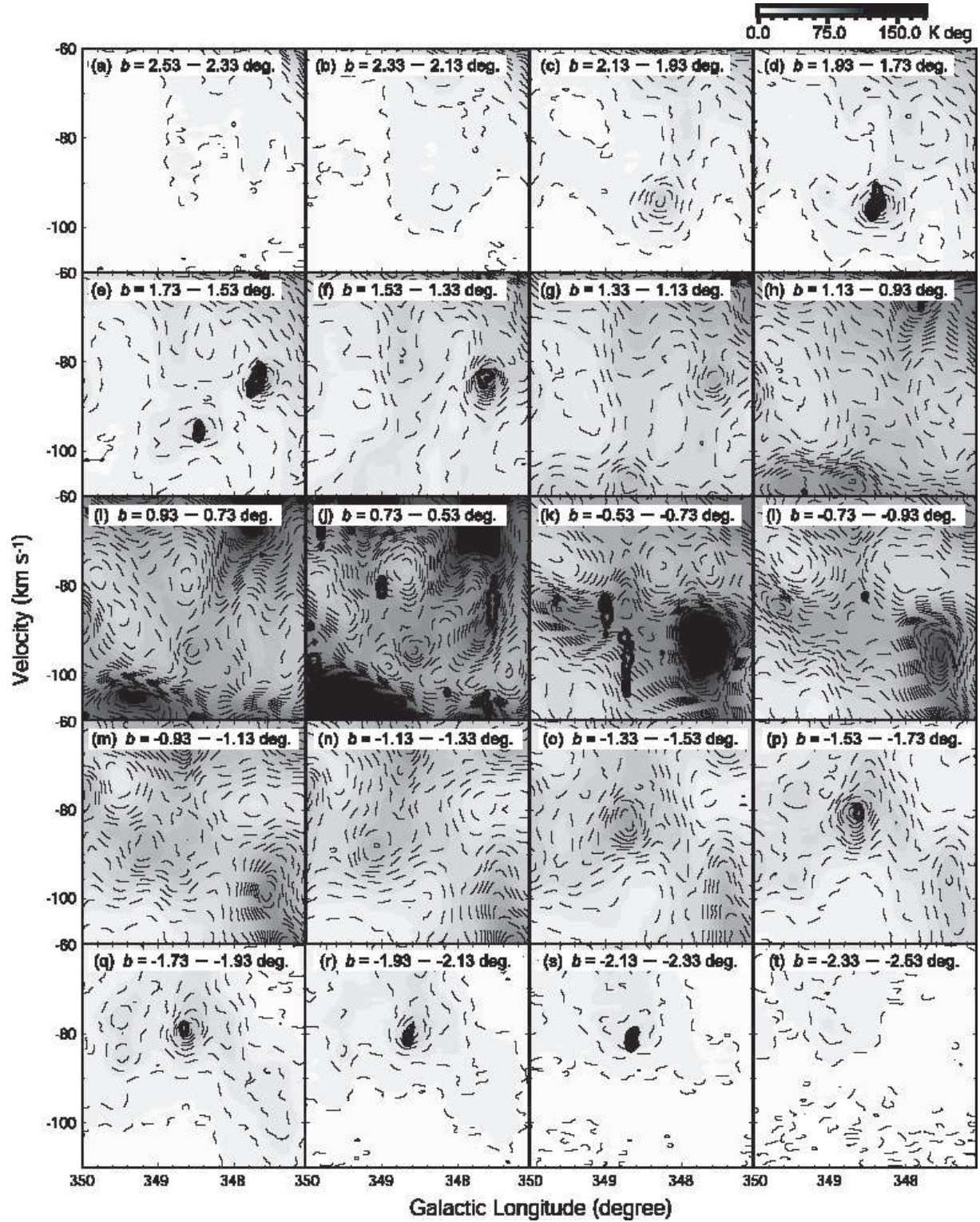


Fig. 9. Channel maps of longitude–velocity diagram from 2.53 to -2.53 degree except within ± 0.53 degree every 0.2 degree in Galactic latitude. The velocity of H I and CO is smoothed at a resolution of 1 km s^{-1} . The range of the galactic latitude is shown in the upper side of each channel map. Gray scale and dashed contours are H I and solid contours are CO. MJG348.5-N, S1, S2, and S3 appear to the channel maps of (d) and (e), (l), (p) and (q), and (r) and (s), respectively. The contour levels of CO and H I are illustrated every 1.5 K degree from 2.0 K degree and every 2.0 K degree every 4.0 K degree, respectively.

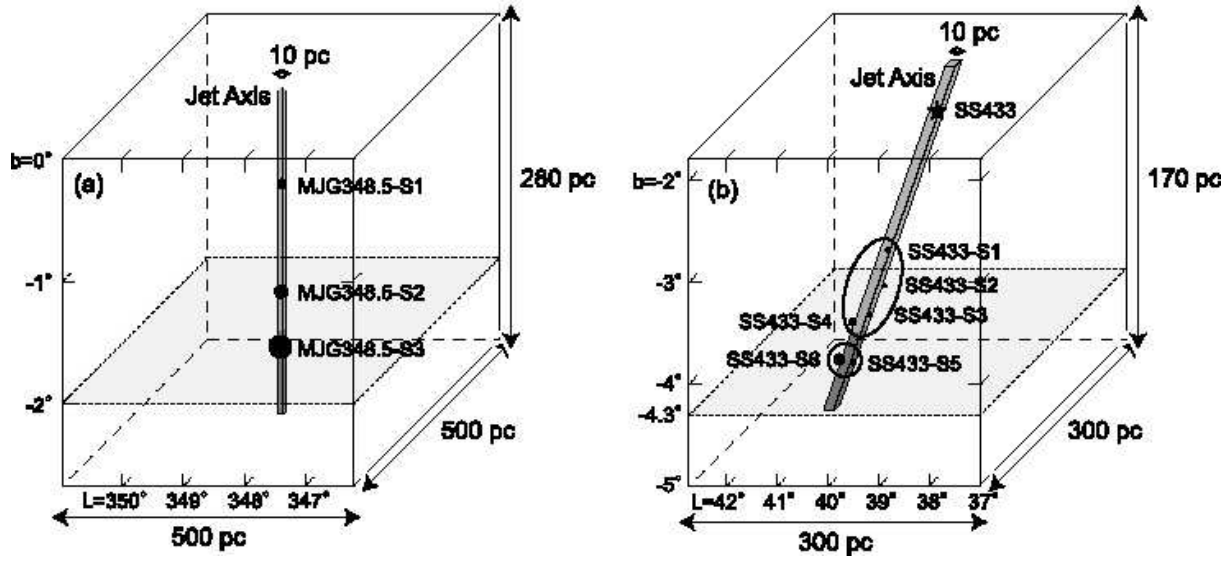


Fig. 10. Schematic view of the space in case of (a) MJG348.5 and (b) SS433. Black filled circles indicate each molecular cloud identified. The planes of (a) $b = -2^\circ$ and (b) $b = -4.3^\circ$ are illustrated by light gray. Gray prisms indicate the direction of the jet. Lower part of the each gray prism in darker gray shows the part lower than (a) $b = -2^\circ$ and (b) $b = -4.3^\circ$.

Table 1. Physical Properties of ^{12}CO Clouds

No.	l ($^{\circ}$)	b ($^{\circ}$)	T_{R}^* (K)	ΔV (km s^{-1})	V_{LSR} (km s^{-1})	$N(\text{H}_2)$ (10^{21} cm^{-2})	R^* (pc)	M_{CO}^* (M_{\odot})	M_{vir}^* (M_{\odot})	t_{cross}^* (Myr)
SS433-N1	39.27	−1.60	4.0	3.1	55.8	3.9	5.1	2500	6000	2.3
SS433-N2	39.33	−1.33	6.0	2.9	53.7	3.0	5.5	3100	14000	1.6
SS433-N3	39.47	−1.53	3.3	1.9	53.0	1.5	3.6	1300	5400	1.3
SS433-N4	39.60	−1.87	10.0	2.3	49.4	4.8	3.6	2100	5000	1.4
SS433-S1	40.53	−3.53	3.9	1.4	42.9	1.4	2.8	600	1200	1.9
SS433-S2	40.53	−3.87	2.7	2.2	45.4	1.4	2.0	400	6400	0.5
SS433-S3	40.80	−4.13	2.9	2.4	44.1	1.7	2.8	900	3300	1.2
SS433-S4	41.13	−4.20	1.8	3.8	43.2	1.5	3.6	1200	21000	0.7
SS433-S5	41.13	−4.60	1.2	4.2	44.8	1.1	2.8	500	16000	0.5
SS433-S6	41.33	−4.53	2.4	2.6	42.1	1.4	5.6	2300	16000	1.6
MJG348.5- N	348.47	1.73	3.3	5.4	−95.0	2.3	12.5	14000	77000	2.3
MJG348.5-S1	348.53	−0.80	1.9	3.4	−82.4	1.6	3.9	1500	9700	1.2
MJG348.5-S2	348.60	−1.67	1.6	3.3	−80.0	1.1	5.6	2000	12000	1.7
MJG348.5-S3	348.67	−2.13	3.2	4.3	−81.3	1.3	9.6	8300	26000	2.2

Col. (1) : Cloud number, Col. (2)–(3) : Cloud peak (l , b) position, Col. (4) : Peak temperature, Col. (5) : Line width of the composite spectrum, Col. (6) : Peak velocity of the composite spectrum, Col. (7) : Column density of peak position, Col. (8) : Radius of the molecular cloud, Col. (9) : Mass of the molecular cloud, Col. (10) : Virial mass of the molecular cloud, Col. (11) : Crossing time of the molecular cloud. Col. (4) to (6) are derived by using a single Gaussian fitting.

* The distance is assumed as 3 kpc on SS433 and 6 kpc on MJG348.5. In details, see Sec. 3.2 and 4.2.

Table 2. List of Supernova Remnants and High Energy Sources toward MJG348.5 in the Galactic Plane*

Name	Positions				Type of Source	Wavelength of detection	Associated Objects
	l	b	$\alpha(J2000)$	$\delta(J2000)$			
G348.5+0.1(CTB37A) [†]	348°39	0°16	17 ^h 14 ^m 6 ^s 0	−38°32′0″	SNR	Radio-Conti. (90cm)	
G348.5-0.0 [†]	348°60	−0°01	17 ^h 15 ^m 26 ^s 0	−38°28′2″	SNR	Radio-Conti. (90cm)	
G348.7+0.3 (CTB37B) [†]	348°65	0°40	17 ^h 13 ^m 55 ^s 1	−38°10′59″	SNR	Radio-Conti. (90cm)	
3EG J1714-3857 [‡]	348°04	−0°09	17 ^h 14 ^m 5 ^s 4	−38°57′54″	γ -ray	γ -ray ($E > 100$ MeV)	
H.E.S.S. J1713-381 [§]	348°65	0°38	17 ^h 13 ^m 58 ^s 1	−38°11′43″	γ -ray	γ -ray ($E > 100$ GeV)	CTB37A, CTB37B, G348.5-0.0
1RXS J171312.8-390553	347°83	−0°03	17 ^h 13 ^m 12 ^s 8	−39°5′54″	X-ray	X-ray	
1RXS J171551.8-385843	348°23	−0°38	17 ^h 15 ^m 51 ^s 9	−38°58′43″	X-ray	X-ray	
1RXS J171557.7-385152	348°33	−0°33	17 ^h 15 ^m 57 ^s 7	−38°51′51″	X-ray	X-ray	
1RXS J171354.4-381740	348°56	0°33	17 ^h 13 ^m 54 ^s 4	−38°17′38″	X-ray	X-ray	CTB37B

* Sources within 1° from $(l, b) \sim (348.5, 0.0)$ are listed[†] Kassim, Baum, & Weiler (1991)[‡] Hartman et al. (1999)[§] Aharonian et al. (2006)^{||} Voges et al. (1999)

Table 3. Physical Parameters of SS433

Velocity*	Mass flow rate [†]	Momentum [‡]	Kinetic power [†]	Timescale [§]
	($M_{\odot} \text{ yr}^{-1}$)	($M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$)	(erg yr^{-1})	(yrs)
$0.26c$	1.5×10^{-7}	1.2×10^{-2}	1.1×10^{46}	2×10^4

* Margon & Anderson (1989)

[†] Marshall et al. (2002)

[‡] (Velocity) \times (Mass flow rate)

[§] Zealey et al. (1980)